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In spite of its extreme importance to the accurate prediction of drag and heating requirements in high-speed flow, the study of boundary-layer transition in hypersonic (NASP) and supersonic (fighter and high-speed civil transport) flows is still very much in its infancy. Transition is well known, however, to depend strongly on such effects as pressure gradient, wall curvature, sweep, roughness, wall mass transfer, freestream and wall temperature, nose radius, nonequilibrium chemistry, and freestream disturbances. (These effects have been discussed in any number of workshops and U.S. Transition Study Group meetings under the direction of Eli Reshotko.)

We have completed detailed studies of the stability of the laminar basic state of 2-D and axisymmetric boundary layers with non-equilibrium chemistry included and 3-D boundary-layer flows of an ideal gas. (Relatively simple geometries were considered due to the anticipated difficulties in performing basic-state analyses.)

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We have completed detailed studies of the stability of the laminar basic state of 2-D and axisymmetric boundary layers with non-equilibrium chemistry included and 3-D boundary-layer flows of an ideal gas. (Relatively simple geometries were considered due to the anticipated difficulties in performing basic-state analyses.) The complete region between the wall and the shock was considered in the non-equilibrium chemistry work.

In 2-D and axisymmetric flows, the inclusion of chemistry caused a shift of the second mode of Mack to lower frequencies. This was found to be due to the increase in size of the region of relative supersonic flow because of the lower speeds of sound in the relatively cooler boundary layers. It was also found that equilibrium and nonequilibrium solutions could be very different depending on the rates of the reactions relative to the time scales of convection and diffusion. In particular, in equilibrium-air calculations, modes which travel supersonically relative to the inviscid region were shown to exist. These modes were a superposition of incoming and outgoing disturbances which exhibited oscillatory behavior because of the finite shock stand-off distance.

For the examination of 3-D effects, a rotating cone was used as a model of a swept wing. An increase of stagnation temperature was found to be only slightly stabilizing. The correlation of transition location (N = 9) with parameters describing the crossflow profile was investigated on the rotating cone. Transition location did not correlate with the traditional crossflow Reynolds number. A new parameter that appears to correlate for boundary-layer flow was found. A verification with the NASA/Langley Mach 3.5 Quiet Tunnel experiments on the yawed cone was done.

TABLE OF CONTENTS

1. INTRODUCTION

In this Final Report, Section 2 documents our technical accomplishments, Sections 3-9 contain more detailed information of the results of our research, Section 10 describes the resources available for the research, and Appendix A contains a short resume for the Principal Investigator.

2. TECHNICAL ACCOMPLISHMENTS

Students: 1 PostDoctoral student, 2 PhD students, 5 MS students, 5 BS students involved in related work

Journal articles: 2 published in *Annual Review of Fluid Mechanics*, 2 published in *Physics of Fluids A*, 2 submitted to *AIAA Journal*, 1 submitted to *Journal of Computational Physics*

Conference papers: 2 invited, 6 other

Conference and industry presentations: 16 invited, 9 other

Publications

1. "Stability of Three-Dimensional Boundary Layers," H.L. Reed and W.S. Saric, *Ann. Rev. Fluid Mech.*, Vol. 21, p. 235, Jan. 1989.
2. "Compressible Boundary-Layer Stability Theory," H.L. Reed and P. Balakumar, *Phys. Fluids A*, Vol. 2, No. 8, p. 1341, Aug. 1990.
3. "Stability of Three-Dimensional Supersonic Boundary Layers," P. Balakumar and H.L. Reed, *Phys. Fluids A*, Vol. 3, No. 4, p. 617, Apr. 1991.
4. "A Catalogue of Linear Stability Theory Results," H.L. Reed, accepted *Ann. Rev. Fluid Mech.*, Vol. 26, 1994.
5. "On the Linear Stability of Supersonic Cone Boundary Layers," G.K. Stuckert and H.L. Reed, accepted *AIAA J*, 1992.
6. "Linear Disturbances in Hypersonic, Chemically Reacting Shock Layers," G.K. Stuckert and H.L. Reed, submitted to *J Comp. Phys.*, 1992.
7. "Transition Correlation in Three-Dimensional Supersonic Boundary Layers," H.L. Reed and T.S. Haynes, in preparation to be submitted to *AIAA J*, 1992.
8. "Stability and Transition of Three-Dimensional Boundary Layers," W.S. Saric and H.L. Reed, *Invited Paper*, AGARD Conference No. 438, *Fluid Dynamics of Three-Dimensional Turbulent Shear Flows and Transition*, Cesme, Turkey, Oct. 1988.
9. "Supersonic/Hypersonic Laminar/Turbulent Transition," H.L. Reed, G.K. Stuckert, and P. Balakumar, *Invited Paper*, in *Developments in Mechanics*, Vol. 15, Proceedings of the 21st Midwestern Mechanics Conference, Aug. 13-16, 1989.
10. "Stability of High-Speed Chemically Reacting and Three-Dimensional Boundary Layers," H.L. Reed, G.K. Stuckert, and P. Balakumar, 3rd IUTAM Symposium on *Laminar-Turbulent Transition*, ed. R. Michel and D. Arnal, Springer-Verlag, New York, 1991.
11. "Stability Limits of Supersonic Three-Dimensional Boundary Layers," H.L. Reed, T. Haynes, and P. Balakumar, *AIAA Paper 90-1528*.
12. "Stability of Hypersonic, Chemically Reacting Viscous Flows," G.K. Stuckert and H.L. Reed, *AIAA Paper 90-1529*.
13. "Unstable Branches of a Hypersonic, Chemically Reacting Boundary Layer," G.K. Stuckert and H.L. Reed, *Royal Aeronautical Society Conference on Boundary-Layer*

Transition and Control, Cambridge UK, April 1991.

14. "Observations in Using Linear Stability Theory for 3-D Supersonic Boundary Layers," H.L. Reed and T.S. Haynes, *Eli Reshotko's 60th Birthday Party*, ICASE and NASA/Langley Research Center, July 28, 1991, to appear 1992.
15. "Stability of Hypersonic Boundary-Layer Flows with Chemistry," H.L. Reed, G.K. Stuckert, and T.S. Haynes, *70th AGARD Fluid Dynamics Panel Symposium* on *Theoretical and Experimental Methods in Hypersonic Flows*, Torino, Italy, May 4-8, 1992.

Presentations

1. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Talk*, Naval Post Graduate School, Monterey, February 18, 1988.
2. "Computational Simulation of Three-Dimensional Boundary-Layer Flows," H.L. Reed, *Invited Lecture*, Tohoku University, Sendai, Japan, April 1988.
3. "Computational Simulation of Three-Dimensional Boundary-Layer Flows," H.L. Reed, *Invited Lecture*, Hokkaido University, Sapporo, Japan, April 1988.
4. "Stability and Transition of Compressible Boundary Layers," H.L. Reed, *Invited Talk*, McDonnell Douglas, St. Louis, May 26, 1988.
5. "Stability and Transition of Three-Dimensional Boundary Layers," W.S. Saric and H.L. Reed, *Invited Paper*, AGARD Conference No. 438, *Fluid Dynamics of Three-Dimensional Turbulent Shear Flows and Transition*, Cesme, Turkey, Oct. 1988.
6. "Energy-Efficient Aircraft," H.L. Reed, *Invited Talk*, Society of Women Engineers, Notre Dame, Nov. 9, 1988.
7. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Talk*, IBM Lecture Series, Notre Dame, Nov. 9, 1988.
8. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Lecture*, University of Western Ontario, London, Canada, Nov. 23, 1988.
9. "Supersonic/Hypersonic Stability," H.L. Reed, *Invited Presentation*, NASA/Langley Research Center, Jan. 30, 1989.
10. "Three-Dimensional Boundary-Layer Stability," H.L. Reed, *Invited Seminar*. Univ Houston, Mar. 2, 1989.
11. "Supersonic/Hypersonic Stability and Transition," H.L. Reed, *Invited Presentation*, General Dynamics/Fort Worth Division, Mar. 17, 1989.
12. "Supersonic/Hypersonic Laminar/Turbulent Transition," H.L. Reed, G.K. Stuckert, and P. Balakumar, *Invited Paper*, in *Developments in Mechanics*, Vol. 15, Proceedings of the 21st Midwestern Mechanics Conference, Aug. 13-16, 1989.
13. "Stability of High-Speed Chemically Reacting and Three-Dimensional Boundary Layers," H.L. Reed, G.K. Stuckert, and P. Balakumar, *3rd IUTAM Symposium on Laminar-Turbulent Transition*, Sept. 1989, Toulouse, ed. R. Michel and D. Arnal, Springer-Verlag, New York, 1991.
14. "Stability of High-Speed Chemically Reacting and Three-Dimensional Boundary Layers," H.L. Reed, *Invited Seminar*, Univ Va, Oct. 26, 1989.
15. "Stability of High-Speed Chemically Reacting and Three-Dimensional Boundary Layers," H.L. Reed, ICASE, NASA/Langley Research Center, Oct. 31, 1989.
16. "Stability of Hypersonic, Chemically Reacting Boundary Layers," G.K. Stuckert and

H.L. Reed, Bull. Amer. Phys. Soc., Vol. 34, No. 10, Nov. 1989.

17. "Transition in High-Speed Flows," H.L. Reed, *Invited Presentation*, H.L. Reed, General Dynamics, Fort Worth, April 9, 1990.
18. "Stability Limits of Supersonic Three-Dimensional Boundary Layers," H.L. Reed, T. Haynes, and P. Balakumar, *AIAA 21st Fluid Dynamics, Plasmadynamics and Lasers Conference, AIAA Paper 90-1528*, Seattle, June 18-20, 1990.
19. "Stability of Chemically Reacting, Hypersonic, Viscous Flows," G.K. Stuckert and H.L. Reed, *AIAA 21st Fluid Dynamics, Plasmadynamics and Lasers Conference, AIAA Paper 90-1529*, Seattle, June 18-20, 1990.
20. "Stability of High-Speed Boundary-Layer Flows," H.L. Reed, T.S. Haynes, and G.K. Stuckert, NASA/Langley Research Center, August 15, 1990.
21. "Crossflow Instability in Supersonic Flow," H.L. Reed and T.S. Haynes, *43th Meeting of the American Physical Society, Division of Fluid Dynamics*, Cornell, *Bulletin American Physical Society*, Volume 35, Number 10, Page 2322, November 1990.
22. "Spinning-Cone Computations," H.L. Reed and T.S. Haynes, *Invited Presentation*, 4th NASP Transition Workshop, NASA/Langley Research Center, December 4, 1990.
23. "Crossflow Calculations for Supersonic Swept Wings," H.L. Reed, *Invited Seminar*, McDonnell-Douglas, St. Louis, May 13-14, 1991.
24. "Stability of High-Speed Flows," H.L. Reed, *Eli Reshotko's 60th Birthday Party*, ICASE and NASA/Langley Research Center, July 28, 1991.
25. "Stability of Hypersonic Boundary-Layer Flows with Chemistry," H.L. Reed, G.K. Stuckert, and T.S. Haynes, *70th AGARD Fluid Dynamics Panel Symposium* on *Theoretical and Experimental Methods in Hypersonic Flows*, Torino, Italy, May 4-8, 1992.

Post Doctoral Associates

P. Balakumar, "Stability of Three-Dimensional Supersonic Boundary Layers," completed Spring 1989.

Ph.D. Students

G. Stuckert, "Linear Stability Theory of Hypersonic, Chemically Reacting Viscous Flows," completed May 1991.

T. Haynes, "Effect of Initial Conditions on Three-Dimensional Supersonic Boundary-Layer Flows," expected Spring 1994.

MS Students

G. Stuckert, "Hypersonic Viscous Flow over Two-Dimensional and Axisymmetric Bodies," completed Spring 1987.

T. Haynes, "Stability Limits of Three-Dimensional Supersonic Boundary-Layer Flows," completed May 1991.

T. (Taylor) Trekas, "Attachment-Line Boundary Layer in High-Speed Flows," Garrett Fellow, expected Summer 1992.

M. Koop, "Effect of Basic State on Three-Dimensional Supersonic Boundary-Layer Stability," Garrett Fellow, expected Summer 1992.

K. Shepherd, "Attachment-Line Instabilities in High-Speed Flows," expected Summer 1992.

Undergraduate Students

T. Haynes, "Stability of Boundary-Layer Flows," completed Fall 1988.

T. Taylor (Trekas), "Stability of High-Speed Flows," completed Summer 1989.

G. Loring, "Secondary Instabilities in Three-Dimensional Boundary Layers," completed Summer 1989.

D. Fuciarelli, "High-Frequency Breakdown in Three-Dimensional Boundary Layers," expected Spring 1992.

M. Petraglia, "Curvature Effects in Three-Dimensional Boundary-Layer Flows," expected Spring 1993.

The basic accomplishments that are described in these publications are outlined below. *This work was invited by Dennis Bushnell to the 4th NASP meeting December 4, 1990 at NASA/Langley Research Center as one of the few efforts in 3-D high-speed transition.*

1. Successful development of hypersonic basic-state Parabolized-Navier-Stokes flow over a flat plate and cone including nonequilibrium chemistry

2. Successful development of 3-D linear-stability code including nonequilibrium chemistry for application to (1). *First results in literature.*

3. Formulate realistic shock boundary conditions for disturbance state.

4. Comparisons of ideal-gas, equilibrium chemistry, and non-equilibrium chemistry results for Mach number 25. *First results in literature.*

5. Successful development of 3-D supersonic basic-state boundary-layer code for flow over a rotating cone. This is a model for crossflow instability.

6. Successful development of 3-D supersonic linear-stability code including curvature for application to (5).

7. Using (6), we find for 3-D boundary layers that the second mode is now oblique and cooling is ineffective for crossflow. *First extensive results in literature.*

8. Successful correlation between a newly formulated crossflow Reynolds number and N = 9 (theoretical transition location) for the rotating cone. Successful verification with the yawed-cone experiments of King in NASA/Langley Mach 3.5 Quiet Tunnel and of Stetson at Mach 5.9 *This is extremely important to industry.*

9. Supersonic attachment-line basic-state calculations underway.

10. Successful development of 3-D supersonic/hypersonic basic-state Parabolized-Navier-Stokes code for flow over a rotating cone. This is a model for crossflow instability and includes nonequilibrium chemistry. These will be extended to real-wing geometries.

11. Parabolized Stability Equations under development for the crossflow instability.

3. LIST OF SYMBOLS

A	$= Pr^{1/2} (\gamma - 1) M_e^2 / 2$
C^*	Chapman-Rubesin parameter based on T^*
C^*_{ad}	Chapman-Rubesin parameter based on T^*_{ad}
E_t	total energy of mixture per unit volume
h_1	$=1 + \kappa y$
h_3	$=(\mathbf{r} + y \cos\varepsilon)^m$
H	factor in R_{cf}(new) including compressibility
H_{cf}	$= \delta_{10} / y_{max}$; crossflow shape factor
i	square root of -1
j_i	molar flux of species *i*
L	factor in R_{cf}(new) including cooling
m	=0 for 2-D flow; =1 for axisymmetric flow
M	freestream Mach number
M_e	local edge Mach number with respect to a reference frame fixed to surface of rotating cone
M_r	local Mach number of basic state relative to velocity at generalized inflection points
M_∞	pre-shock Mach number
N	amplification factor
p	pressure; mixture pressure
Pr	Prandtl number at the reference temperature T^*
q	general basic-state quantity
q_x,q_y,q_z	heat flux
q_0	general disturbance-amplitude distribution
q_1	general disturbance quantity
$\mathbf{r}$	distance from body axis to surface
r	$= T_{w0} / T_{a0}$
R	Reynolds number based on local edge conditions and reference boundary-layer thickness
R_{cf}	$= W_{max}\delta_{10}/\nu$; traditional crossflow Reynolds number
$R_{cf(new)}$	new crossflow Reynolds number, Eq. (1)
Re_L	Reynolds number based on a reference length
R_t	R at transition according to linear stability theory
R_0	R at x_0
S, S_{ij}	stress tensor
t	time
T	temperature
T_{ad}	local adiabatic wall temperature
T_{a0}	adiabatic wall temperature at upstream point x_0
T_e	edge temperature
T_{w0}	specified wall temperature at upstream point x_0
T_w	local wall temperature
T^*	reference temperature
T^*_{ad}	reference temperature for adiabatic wall
u,v,w	streamwise, normal-to-wall, spanwise velocity
U_e	local inviscid flow speed; for rotating cone, reference frame is fixed to the surface
W_{max}	maximum crossflow velocity, that is, velocity in direction perpendicular to local inviscid flow; for rotating cone, reference frame is fixed to surface
x,y,z	streamwise, normal-to-wall, spanwise coordinates
x_0	initial streamwise position for calculation of N; or upstream position for marching
y_{max}	height of W_{max} above wall
y_1	height of relative sonic point above wall
α	streamwise component of wavenumber
$-\alpha_I$	negative of imaginary part of α; spatial growth rate

β	spanwise component of wavenumber
β_I	imaginary part of β
δ	boundary-layer thickness
δ_{ad}	boundary-layer thickness for adiabatic wall
δ_{cool}	boundary-layer thickness for cooled wall
δ_{incomp}	boundary-layer thickness for incompressible constant-temperature flow
δ_r	$= (\mu_e x/\rho_e U_e)^{1/2}$; reference boundary-layer thickness
δ_{10}	height above y_{max} where crossflow is 10% W_{max}
ε	angle between body surface and body axis
γ	edge ratio of specific heats
γ_∞	pre-shock ratio of frozen specific heats
η	either a similarity or computational variable in normal-to-wall direction
κ	$= -d\varepsilon / dx$
μ_e	edge dynamic viscosity
ν_e	edge kinematic viscosity
θ	cone angle
ρ	mixture mass density
ρ_e	edge density
σ_i	ratio of species *i* concentration to mixture mass density
τ	time variable in computational domain
ω	frequency of disturbance
Ω	cone rotational speed
ξ,η,ζ	streamwise, normal-to-wall, spanwise computational coordinates

4. MOTIVATION

The skin-friction drag and heat-transfer rates of hypersonic and supersonic vehicles can be reduced by delaying transition from laminar to turbulent flow. But the physical characteristics of transition at these speeds are not well known. Transition *is* known, however, to be highly dependent on the details of the flowfield.

Hypersonic and supersonic flows are further complicated over incompressible flows for some of the following reasons. 1) At these speeds, the gas often cannot be modeled as perfect because the molecular species begin to dissociate due to aerodynamic heating. In fact, sometimes there are not enough intermolecular collisions to support local chemical equilibrium and a nonequilibrium-chemistry model must be used. 2) The bow shock is very close to the edge of the boundary layer and must be included in the calculations. 3) Because of the speeds, the wings are highly swept and the boundary layers are highly 3-D. These effects must be included in any studies of transition.

Linear stability theory proves useful in determining the important effects and their trends. Here, the resultant growth or decay of small disturbances in the boundary layer which lead to transition is the measure of transition enhancement or delay. This paper reports the results of linear stability theory applied to chemically reacting flows with finite shock stand-off distance in Section 5 and 3-D flows in Section 6.

5. CHEMICALLY REACTING TWO-DIMENSIONAL BOUNDARY LAYERS

5.1 Numerical Approach

Qualitative as well as quantitative differences in the linear stability of the shock layer on a sharp cone can be observed when the effects of finite-rate chemical reactions are included in the analysis. Here a five-component model for dissociated air is used: O_2, N_2, NO, N, and O. Only the effects of dissociation are considered; those of ionization are not. The mixture is also assumed to be one of ideal gases in thermal equilibrium.

The equations governing the flow of this reacting-gas mixture are originally expressed in the body-intrinsic coordinate system (i.e., Anderson et al., 1984). However, since the boundary layer occupies a substantial fraction of the shock layer at hypersonic speeds, these equations are transformed into a coordinate system where the basic-state bow shock is a boundary of the computational domain:

$$\partial(y_\eta Q)/\partial\tau + \partial(y_\eta E)/\partial\xi + \partial(-y_\tau Q - y_\xi E + F - y_\zeta G)/\partial\eta + \partial(y_\eta G)/\partial\zeta + y_\eta H - y_\eta R = 0$$

where

$$Q = h_1 h_3 \{\rho, \rho u, \rho v, \rho w, E_t, \rho\sigma_i\}$$

$$E = E_I - E_V$$

$$E_I = h_3 \{\rho u, \rho u^2 + p/\gamma_\infty M_\infty^2, \rho uv, \rho uw, (E_t+p)u, \rho\sigma_i u\}$$

$$E_V = (h_3/Re_L)\{0, S_{xx}, S_{yx}, S_{zx}, \gamma_\infty M_\infty^2 (uS_{xx} + vS_{yx} + wS_{zx}) - q_x, -j_{ix}\}$$

$$F = F_I - F_V$$

$$F_I = h_1 h_3 \{\rho v, \rho uv, \rho v^2 + p/\gamma_\infty M_\infty^2, \rho vw, (E_t+p)v, \rho\sigma_i v\}$$

$$F_V = (h_1 h_3/Re_L)\{0, S_{xy}, S_{yy}, S_{zy}, \gamma_\infty M_\infty^2 (uS_{xy} + vS_{yy} + wS_{zy}) - q_y, -j_{iy}\}$$

$$G = G_I - G_V$$

$$G_I = h_1 \{\rho w, \rho uw, \rho vw, \rho w^2 + p/\gamma_\infty M_\infty^2, (E_t+p)w, \rho\sigma_i w\}$$

$$G_V = (h_1/Re_L)\{0, S_{xz}, S_{yz}, S_{zz}, \gamma_\infty M_\infty^2 (uS_{xz} + vS_{yz} + wS_{zz}) - q_z, -j_{iz}\}$$

$$H = H_I - H_V$$

$$H_I = \{0, \kappa h_3 \rho uv - mh_1 (\rho w^2 + p/\gamma_\infty M_\infty^2)\sin\varepsilon, -\kappa h_3 (\rho u^2 + p/\gamma_\infty M_\infty^2) - mh_1 (\rho w^2 + p/\gamma_\infty M_\infty^2)\cos\varepsilon, mh_1 \rho w (u\sin\varepsilon + v\cos\varepsilon), 0, 0\}$$

$$H_V = \{0, \kappa h_3 S_{xy} - mh_1 S_{zz}\sin\varepsilon, -\kappa h_3 S_{xx} - mh_1 S_{zz}\cos\varepsilon, mh_1 (S_{xz}\sin\varepsilon + S_{yz}\cos\varepsilon), 0, 0\}$$

$$R = h_1 h_3 \{0, 0, 0, 0, 0, \text{Molar rate of production of species } i\}$$

(Note: E, F, G, H, Q, R are not in the List of Symbols.) The viscosity used to determine the viscous stress tensor **S** is computed using the mixture laws of Brokaw (1958). The translational thermal conductivity is computed similarly, whereas the internal thermal conductivity is determined as described in Hirschfelder (1957). The molar fluxes $\mathbf{j}_i$ are computed using the multicomponent diffusion model described by Curtiss & Hirschfelder (1949), but only diffusion due to concentration gradients is included - diffusion due to pressure gradients, temperature gradients, and body forces is not. Finally, the law of mass action is used to compute the molar rate of production of each species assuming that they participate in the following elementary reactions:

$$O_2 + M \leftrightarrow O + O + M$$

$$N_2 + M \leftrightarrow N + N + M$$

$$N_2 + O \leftrightarrow NO + N$$

$$O + NO \leftrightarrow N + O_2$$

where M is a collision partner (any of the species present in the mixture) which transfers energy in a reaction.

The thermophysical data needed for the analysis have been taken from a variety of sources. Collision cross section data for the transport properties can be found in Biolsi & Biolsi (1983), Biolsi (1988), Capitelli & Devoto (1973), Capitelli & Ficocelli (1972), Cubley & Mason (1975), Levin et al. (1987, 1988), Monchick (1959), and Yun & Mason (1962). Thermodynamic data have been taken from Blottner et al. (1971) and Jaffe (1987). Reaction-rate data can be found in Camac & Vaughan (1961), Wray (1962), Thielen & Roth (1986), Monat et al. (1978), and Hanson & Salimian (1984). Reverse reaction-rate constants are computed using the law of detailed balance to express them in terms of the forward-rate constants and the equilibrium constants. For a complete description of the constitutive equations as well as detailed references for the thermophysical data, refer to Stuckert (1991).

5.1.1 Basic State

The basic state is computed using the Parabolized Navier-Stokes equations, which are obtained from those given above by neglecting viscous terms involving derivatives tangent to the body. (To simplify the analysis, this approximation is made in the body-intrinsic coordinate system before the equations are transformed into the shock-fit coordinate system.) The Beam-Warming algorithm (Beam & Warming, 1978) is used in conjunction with a shock-fitting scheme and the Vigneron technique (to suppress *departure* solutions) to solve these equations. This is an efficient implicit algorithm used to march the solution downstream from initial conditions generated here by assuming that the flow is approximately conical near the apex of a sharply pointed body. A stretching function is used to cluster grid points near the edge of the boundary layer - a location where the basic state varies rapidly and which also lies in the vicinity of the critical point of the disturbance state at hypersonic Mach numbers. No artificial dissipation is required for the simple geometry investigated here because there are no discontinuities embedded in the shock layer.

5.1.2 Linear Stability Theory

The linear stability analysis for each of these cases is performed by linearizing the complete Navier-Stokes equations about the basic state. The same basic-state shock-fit coordinate system is used (which is almost conical) and linearized inviscid shock jump conditions are imposed at the basic-state shock location. For a cone, though, $\kappa \equiv 0$, and so $h_1 \equiv 1$. Normal modes are assumed for the disturbance state variables q_1:

$$q_1 = q_0(\eta) \exp\{i(\alpha\xi + \beta\zeta - \omega\tau)\}$$

and the basic-state flow is assumed to satisfy $\partial q/\partial\xi \equiv 0$. (Note that the basic-state normal-velocity component is *not* set to zero; it is not zero in a conical flow.) The disturbances in velocity and temperature as well as species mass fluxes (i.e., noncatalytic wall) are zero at the surface. (For equilibrium air analyses, the disturbances are assumed to be in chemical equilibrium at the surface.) These homogeneous equations and boundary conditions represent an eigenvalue problem for the eigenvector $q_0(\eta)$. When α and β are specified, the eigenvalue is ω (temporal problem), and when β and ω are specified, the eigenvalue is α (spatial problem). In either case, the governing equations are first discretized using second-order accurate central differences. The temporal problem is easy to analyze because it is linear in ω and hence can be solved using a globally convergent scheme such as the QZ algorithm (e.g., Golub & VanLoan, 1985). Inverse iteration and the Newton-Raphson method can then be used to compute the eigenvector and solve the spatial eigenvalue problem.

5.2 Results

The particular case investigated is that of a 10° half-angle cone flying at 8100 m/s and zero angle of attack at an altitude of 60.96 km where the ambient temperature and pressure are 252.6K and 2.008×10^{-4} atmospheres, respectively. The Reynolds number based upon a reference length of 1m and these freestream conditions is 139,900. The atmosphere is considered to be 21% O_2 and 79% N_2 by volume, and the noncatalytic surface of the cone is kept at a constant temperature of 1200K. This is essentially the case considered by Prabhu et al. (1988) except that they assumed a different freestream composition of air. Also, there is no crossflow.

Due to the lack of space, only a couple of basic-state results pertinent to the stability analysis are presented here. It should be mentioned, though, that the boundary-layer edge Mach number is approximately 10 for the given pre-shock conditions. It is slightly higher for the perfect-gas analysis, and slightly lower for the equilibrium- and nonequilibrium-air analyses because the hotter perfect-gas boundary layer is more rarefied and hence thicker, displacing and compressing the external flow the greatest. Similarly, the perfect-gas edge temperature is approximately 6.5 times the freestream temperature, whereas the equilibrium- and nonequilibrium-air edge temperatures are closer to 6 times the freestream temperature.

One feature of the boundary layer important to the linear stability is the *size* of the region where the disturbance state is supersonic relative to the local basic state. A measure of this is

$$\int_0^{y_1} (M_r^2-1)^{1/2}\, dy$$

where M_r is the local Mach number of the basic state relative to the velocity at the generalized inflection points (those points where $\partial(\rho\partial u/\partial y)/\partial y = 0$). This integral is shown in Figure 1 (where x is measured in meters). Corresponding results from a perfect-gas boundary-layer similarity solution are also shown for comparison. One can see from this figure that the perfect-gas similarity solution and PNS solution yield very comparable results and that in both cases the values of the integrals are substantially less than the corresponding values for the equilibrium- and nonequilibrium-air boundary layers. As Mack (1969) has shown, this integral is closely related to the spacing between his higher inviscid modes; as an approximation, it is inversely proportional to it. The shift to lower frequencies of the most unstable second-mode disturbance when the effects of equilibrium-air chemistry are included has been seen by both Malik (1989) and Stuckert (1991). See Figure 2. The same shift in frequency is observed in the nonequilibrium case for precisely the same reason: the local relative Mach number is in general higher for the reacting-gas cases because the local velocity is almost the same, but the local speed of sound is lower in the colder boundary layers. These reacting-gas boundary layers are colder because some of the heat generated by viscous dissipation is used to dissociate the molecular oxygen and nitrogen.

The equilibrium-air boundary layer also exhibits a feature which is not seen in the perfect gas or the nonequilibrium-air boundary layer (at least for the present flight conditions). In particular, an equilibrium-air mode exists which is supersonic relative to the inviscid region of the shock layer. The eigenfunction for this disturbance is shown in Figure 3. The oscillatory behavior of the magnitude of the disturbance is due in part to the fact that the character of the disturbance-state equations changes when the Mach number of the disturbance is supersonic relative to the boundary-layer edge. It is also due to the fact that the shock is a finite distance away from the surface. Since the shock stand-off distance is finite, solutions to the disturbance-state equations in the inviscid region of the shock layer are possible which do not decay as y becomes large. This is discussed in greater detail by Stuckert & Reed (1992).

6. THREE - DIMENSIONAL HIGH - SPEED BOUNDARY LAYERS

6.1 Use of Simple Geometries to Model Three-Dimensional Boundary Layers

At hypersonic and supersonic speeds, the wings of the vehicles are highly swept and the flow is highly 3-D. When a boundary-layer flow is fully 3-D, the stability and transition behavior is quite different from 2-D flows. Of particular interest are the stability characteristics of these 3-D flows where inviscid criteria may produce a stronger instability (crossflow instability) than the usual Tollmien-Schlichting waves (T-S waves). For a recent review of this subject, see Reed & Saric (1989).

Examples of other 3-D flows of practical interest include rotating cones, yawed cylinders and cones, corners, inlets, and rotating disks. It appears that all of these flows (including swept wings) exhibit the same rich variety of stability behavior that is generic to 3-D boundary layers. A consistent characteristic of the instabilities is the presence of streamwise vorticity within the shear layer.

In fact, in incompressible flow, for example, the experimental and analytical results of Kobayashi et al. (1983) on rotating cones have demonstrated that one can even *model* a swept wing or other more complicated geometry exhibiting crossflow instability by a simpler geometry and study the stability characteristics. Results obtained can thus be directly applied to other 3-D boundary layers. From simpler geometries such as the rotating cone, much of what is known about the flow over the swept wing has been learned.

6.2 Numerical Approach

To evaluate parameters quantifying stability characteristics, the linear stability of the flow over a rotating cone at zero incidence is examined. As mentioned above, this is a simple geometry that is often used very successfully in incompressible flow as a model for a swept wing. At very high speeds, where even the basic-state calculations are a problem, the simple geometry of the rotating cone becomes a suitable and valuable model to study the crossflow instability (Balakumar & Reed, 1991).

The geometry considered is that of a sharp cone located in a uniform high-speed stream at zero angle of attack and rotating about its axis (Figure 4). The governing boundary-layer equations for a compressible ideal-gas flow are solved in a body-oriented coordinate system. By varying the freestream Mach number, rotational speed, cone angle, and position on the cone, a wide parameter range of possible 3-D boundary layers can be studied and the various non-dimensional parameters associated with the crossflow profile are easily fixed (R, R_{cf}, H_{cf}, . . .). The details of the basic-state formulation and linear stability analysis are available in Balakumar & Reed (1991).

6.3 Linear Stability Theory Results

Calculations were completed at different edge Mach numbers M = 1.5, 3.0, 5.0 and 8.0 and Reynolds numbers R = 600, 1000, 2000, 3000 for a cone of half angle 15° at a non-dimensional rotational speed of 0.375 by Balakumar & Reed (1991). To summarize, they find at all Mach numbers that the maximum amplified crossflow is nonstationary with the frequency increasing with Mach number from approximately 5 kHz at M=1.5. There exist neutral and unstable stationary waves but the amplification rate is very small compared to the positive frequency.

At M = 1.5, the direction of the most amplified crossflow is 55° at R = 600 increasing to 65° at R = 3000. As R increases further the angle approaches that of the crossflow direction of 73.8°. A similar observation occurs for other Mach numbers.

At M = 5.0, for which the 2-D second mode has been observed to clearly dominate the first mode in the flat-plate boundary layer, they find a competition between the crossflow and second mode. At R = 600, the maximum amplification rate of the crossflow is higher than the maximum amplification rate of the 2-D second mode; see Figure 5 (from Balakumar & Reed, 1991). As Reynolds number increases, even though the amplification rate of the crossflow increases, it is eventually less than the maximum amplification of the second mode. As Mach number is increased, the second mode dominates earlier.

Further results show that the most unstable second mode in a 3-D boundary layer is actually oblique whereas the second mode in a 2-D boundary layer is 2-D; this is also shown in Figure 5 where the *2-D* direction is -16.2°. The most unstable second mode is inclined at 5° to the inviscid flow direction at M = 5 and is inclined at 9° at M = 8. However, the difference between the amplification rates in the most amplified direction and in the inviscid flow direction is small, on the order of 2%.

Cooling the wall does not affect the crossflow instability. For M = 5, Figure 6 (from Balakumar & Reed, 1991) shows the variation of the critical Reynolds number (at which an instability first appears) versus crossflow Reynolds number (achieved by varying rotational speed, a larger value corresponds to stronger three-dimensionality) for different wall conditions r = T_{w0}/T_{a0} = 1.0, 0.8, and 0.5. As expected, the critical Reynolds number of the first mode increases and the critical Reynolds number of the second mode decreases with wall cooling and confirms the result that wall cooling stabilizes the first mode and destabilizes the second mode. However, for the first mode, it is seen that the critical Reynolds number decreases with increasing crossflow Reynolds number and at large crossflow Reynolds number, the critical Reynolds numbers all approach the same value regardless of the status of the boundary layer. This is observed for all Mach numbers and Reynolds numbers tested. Similar results have been seen by Lekoudis (1980), Mack (1980), and Bushnell & Malik (1987).

6.4 Transition Prediction and Correlation Parameters

The state-of-the-art transition-prediction method still involves linear stability theory coupled with an e^N transition-prediction scheme (Mack, 1984; Poll, 1984) and is applied at all speeds (Bushnell et al., 1989). N is the result of the integration of the linear growth rate from the first neutral-stability point to a location somewhere downstream on the body. Thus e^N is the ratio of the amplitudes at the two points and the method correlates the transition Reynolds number with N.

Aside from the e^N method along with various modifications (e.g., Cebeci et al., 1988), several past investigators have identified non-dimensional parameters quantifying the characteristics of the crossflow instability for boundary-layer profiles and, in some cases, attempted to correlate these numbers with transition location. Some examples follow.

In subsonic flow, Owen & Randall (1952) introduced a crossflow Reynolds number $R_{cf} = W_{max}\delta_{10}/\nu_e$ as the governing parameter and suggested that transition occurs when the crossflow Reynolds number becomes equal to 175. Pfenninger (1977) used crossflow shape factor $H_{cf} = y_{max}/\delta_{10}$ and crossflow Reynolds number in the design of supercritical airfoils. Dagenhart (1981) then considered stationary crossflow vortices and, instead of solving the linear-stability equations each time, he used a table lookup of growth rates based on the profile characteristics: crossflow shape factor and crossflow Reynolds number. He then integrated these interpolated values to obtain N-factors. He reported that his code MARIA adequately reproduces the stability results of the more complicated stability codes using the same physical disturbance model while using less than two percent of the computer time.

In supersonic flow, Chapman (1961) and Pate (1978) made similar conclusions that crossflow Reynolds number correlates well with transition location. On a yawed cone, King (1991) found that there was no correlation with the traditional definition of crossflow Reynolds number. However, when he reformulated this parameter to include both compressibility and yawed-cone geometry effects, he found a good correlation for both his and Stetson's (1982) data.

6.4.1 Numerical Approach

With the current interest in high-speed flight, there is also a keen desire to determine correlating parameters, *based purely on basic-state profiles*, that can be easily incorporated into existing basic-state codes and will *accurately* predict transition location (or trends) for crossflow-dominated problems. To evaluate appropriate parameters quantifying stability characteristics, the linear stability of the flow over a rotating cone at zero incidence is again examined. Results are then applied to available experimental data on other geometries.

Locally, for a given frequency, the maximum growth rate $-\alpha_I$ is found and β_I=0. For each frequency, then, the amplification factor N is determined by integrating the growth rate in the streamwise direction x from the Branch I location x_0. With the Reynolds numbers at x_0 and x being R_0 and R, respectively,

$$N = -2 \int_{R_0}^{R} \alpha_I \, dR.$$

To evaluate transition location, all possible frequencies are sampled to determine where each individual disturbance achieves $N = 9$. The most upstream of this locus of streamwise locations is deemed the estimated transition location. The values of other non-dimensional parameters characterizing crossflow may then be evaluated against the results of $N = 9$.

6.4.2 Compressibility Effects

White (1974) points out that to estimate the boundary-layer thickness for a flat plate, one should consider the similarity variable so that

$$\delta R / x = \int_0^{\eta(\delta)} (T/T_e)\, d\eta$$

To extend this to a more general situation, then, a 3-D compressible boundary-layer, δ, should thicken with respect to the corresponding incompressible layer, δ_{incomp}, according to

$$\delta / \delta_{incomp} = \int_0^{\eta(\delta)} (T/T_e)\, d\eta / \eta$$

Looking at the right hand side of the last equation, δ_{incomp} is a constant-temperature incompressible value. The estimated thickness then of a cooled-wall boundary layer, δ_{cool}, to that of an adiabatic wall, δ_{ad}, is (White 1974, Reed & Haynes 1992).

$$\delta_{cool} / \delta_{ad} = (C^* / C^*_{ad})^{1/2} (3.279 + 1.721\, [T_w / T_{ad}]\, [1 + A] + 0.664\, A) / (5 + 2.385\, A)$$

where

$$A = Pr^{1/2} (\gamma - 1)\, M_e^2 / 2$$

$$C^* = (T^* / T_e)^{1/2} (1 + 110.4 / T_e) / ([T^* / T_e] + 110.4 / T_e)$$

$$C^*_{ad} = (T^*_{ad} / T_e)^{1/2} (1 + 110.4 / T_e) / ([T^*_{ad} / T_e] + 110.4 / T_e)$$

$$T^* / T_e = 0.5 + 0.5\, T_w / T_e + A / 6$$

$$T^*_{ad} / T_e = 0.5 + 0.5\, (1 + A) + A / 6$$

and the Chapman-Rubesin parameter is approximated as a constant C^* across the boundary layer. Because the incompressible crossflow Reynolds number correlates reasonably well for incompressible flows, a new general definition for R_{cf}, then, is

$$R_{cf}(new) = H\, L\, R_{cf} = H\, L\, W_{max}\, \delta_{10} / \nu_e \tag{1}$$

where

$$H = \eta(\delta_{10}) / \int_0^{\eta(\delta_{10})} (T/T_e)\, d\eta$$

$$L = (C^* / C^*_{ad})^{1/2} (3.279 + 1.721\, [T_w / T_{ad}]\, [1 + A] + 0.664\, A) / (5 + 2.385\, A)$$

and all temperatures are in K and $\eta(\delta_{10})$ is the value of η at δ_{10}. The quantity δ_{10} has been scaled back to an incompressible value with the inclusion of the new factor H. To compensate for a cooled wall, then, the factor L is used. Note that, because one is taking the ratio of two normal-to-the-wall lengths, the new factor H is easily computed no matter what the scaling is for the normal-to-the-wall coordinate. Note also that R_{cf}(new) reduces to R_{cf} for incompressible, adiabatic-wall flows.

6.4.3 Results

Using the traditional formulations for crossflow Reynolds number and shape factor

$$R_{cf} = W_{max}\, \delta_{10} / \nu \qquad (2)$$

$$H_{cf} = y_{max} / \delta_{10},$$

Figure 7 shows the attempt at transition correlations for an upstream Mach number of M = 3 and various cone angles θ, rotational speeds Ω, and wall and freestream temperatures T_w and T_e. The various flow conditions represented are documented in Table 1. The spread in R_{cf} is on the order of 200% and is therefore not useful for design. Figure 8 shows the same data plotted considering transition Reynolds number R_t versus rotational speed Ω (with increasing Ω implying increasing 3-D effects). Cooling is only slightly stabilizing (see also Lekoudis 1980, Mack 1980, Bushnell & Malik 1987, and Balakumar & Reed 1991) and an increase of stagnation temperature has an even smaller stabilizing effect. Even so, these temperature effects produce large changes in R_{cf}.

Table 1 Rotating-cone configurations for M = 3

Set	Fixed Parameters	Varied Parameters and Range
I	Ω=0.375 T_e=70K adiabatic wall	θ from 10° to 35°
II	Ω=0.25 T_e=70K adiabatic wall	θ from 10° to 20°
III	θ=15° T_e=70K adiabatic wall	Ω from 0.1 to 0.8
IV	θ=15° T_e=260K adiabatic wall	Ω from 0.1 to 0.8
V	Ω=0.375 T_e=260K adiabatic wall	θ from 10° to 35°
VI	θ=15° T_e=70K cooled wall	Ω from 0.1 to 0.8
VII	θ=15° T_e=260K cooled wall	Ω from 0.4 to 0.8

Table 2 shows comparative results for upstream freestream Mach numbers of M = 0.01, 3, and 6 for different freestream-temperature (T_e) and surface-temperature (T_w/T_e) conditions and a wide variety of rotating-cone geometries. The Mach-3 (M = 3) conditions correspond to those in Figure 7 and Table 1. The results of the new definition for crossflow Reynolds number with compressibility effects included, R_{cf}(new) [Eq. (1)], are contrasted with those obtained from the traditional definition, R_{cf} [Eq. (2)]. Also included is the maximum crossflow velocity in $\%U_e$; the significance of this should become apparent in the subsequent discussion.

Figure 9 shows all the rotating-cone data from Table 2 for M = 0 and 3 plotted. There appears to be a relationship between maximum crossflow velocity and the new crossflow Reynolds number, Eq. (1), proposed above. Also, the new compressible values are consistent with the incompressible value.

Table 2

M	M_e	T_e(K)	T_w/T_e	R_{cf}	R_{cf}(new)	W_{max}/U_e(%)
.01	.01	300	1	165	165	5.9
3	3.1	70	2.6	241	119	3.2
3	3.2	70	2.7	311	149	4.5
3	3.4	70	2.9	373	170	5.7
3	3.6	70	3.2	409	175	6.1
3	3.8	70	3.5	428	171	6.1
3	3.1	260	2.5	210	107	2.6
3	3.1	260	2.6	263	132	3.6
3	3.2	260	2.7	316	154	4.8
3	3.4	260	2.9	366	168	5.9
3	3.7	260	3.2	388	166	6.1
3	3.9	260	3.5	400	161	6.0
3	3.2	70	1.5	339	177	4.6
3	3.3	70	1.5	354	179	5.5
3	3.6	70	1.5	354	168	6.1
3	3.8	70	1.5	344	155	6.1
3	4.1	70	1.5	332	140	5.8
3	4.2	260	1.5	448	201	5.6
3	3.8	260	1.5	323	156	6.0
3	4.1	260	1.5	310	142	5.7
6	9.2	70	14.8	2483	255	5.0
6	9.2	260	17.1	2176	217	5.0
6	7.4	70	9.7	2101	309	6.1
6	7.3	70	4.4	1442	247	6.1

Because linear stability theory with N = 9 applied to a rotating cone was used to find this trend, it is important to verify it against experimental data. The most reliable, available, high-speed 3-D transition data to these authors' knowledge is that of King (1991) on the yawed cone in the Mach 3.5 Quiet Tunnel at NASA/Langley. The King experiment was on a 5° half-angle cone yawed at 0.6°, 2°, and 4°. The data of transition locations for various freestream conditions, both quiet and noisy, are documented in King (1991).

Later, King provided the present authors with the computational mean-flow profiles he used in the analysis of his experimental results. Applying the traditional definition of crossflow Reynolds number, Eq. (2), gives values ranging from 80 to 640 for quiet conditions and 60 to 560 for noisy conditions. King found a correlation for his data when both a geometry and compressibility correction were applied. The new parameter proposed in the present paper contains no geometry factor explicitly. Applying the new crossflow Reynolds number, Eq. (1), to these same profiles results in Figure 10.

King (1991) also considered the M = 5.9 experiments of Stetson (1982) on a 8° half-angle cone yawed at 1°, 2°, and 4° and again provided the present authors with the mean-flow profiles he used in the evaluation of this experiment. Considering what Stetson terms as the beginning of transition, applying the traditional definition of crossflow Reynolds number, Eq. (2), gives values ranging from 140 to 780. The results, then, of applying the new crossflow Reynolds number, Eq. (1), to these profiles are also found in Figure 10. The surface of Stetson's cone was cooled, the wall of King's cone was adiabatic. The Stetson data were taken with a noisy freestream.

The trends of the three sets of data in Figure 10 suggest a least squares fit for the correlation of R_{cf}(new) and W_{max}:

Quiet (M=3.5)

$$R_{cf}(\text{new}) = 26.7 + 38.0\ W_{max}/U_e$$

Noisy (M=3.5)

$$R_{cf}(\text{new}) = 14.7 + 33.9\ W_{max}/U_e$$

Noisy (M=5.9)

$$R_{cf}(\text{new}) = 26.5 + 25.2\ W_{max}/U_e$$

where W_{max}/U_e is in %. The three curves are plotted in Figure 11. Below the curves, the flow has not undergone transition. The values of R_{cf}(new) are consistent with the incompressible values found in the literature. It is also surprising that the Stetson data agrees so well with the King noisy data.

7. CONCLUSIONS

The effects of nonequilibrium chemistry and three-dimensionality on the stability characteristics of hypersonic and supersonic flows have been discussed.

In 2-D and axisymmetric flows, the inclusion of chemistry causes a shift of the second mode of Mack to lower frequencies. This is found to be due to the increase in size of the region of relative supersonic flow because of the lower speeds of sound in the relatively cooler boundary layers.

It is also found that equilibrium and nonequilibrium solutions can be very different depending on the rates of the reactions relative to the time scales of convection and diffusion. In particular, in equilibrium-air calculations, modes which travel supersonically relative to the inviscid region are shown to exist. These modes are a superposition of incoming and outgoing disturbances which exhibit oscillatory behavior because of the finite shock stand-off distance.

For the examination of 3-D effects, a rotating cone is successfully used as a model of a swept wing. A large parameter range of flow conditions can be studied and trends observed. The value of this should become more apparent from the subsequent paragraphs.

The amplification rate of the first mode is increased by a factor of 2 to 4 due to the presence of the crossflow.

The most unstable crossflow instability has a nonzero frequency.

The second mode in a 3-D boundary layer is found to be oblique whereas the second mode in a 2-D boundary layer is 2-D.

Cooling is found to be ineffective in controlling crossflow.

Considering a perfect gas, increasing freestream stagnation temperature only slightly stabilizes the crossflow instability.

For the rotating cone, transition location (N = 9) does not correlate with the traditional crossflow Reynolds number. When compressibility and cooling effects are included, Eq. (1), a relationship exists between the new crossflow Reynolds number and the maximum crossflow velocity at transition. This result has been verified with the yawed-cone data of King (1991) and Stetson (1982). The new crossflow Reynolds number is calculated solely from the basic-state profiles and, as such, it can aid in transition prediction and design for 3-D boundary layers. This formula contains no geometry explicitly and applies for flows with Prandtl number different from unity.

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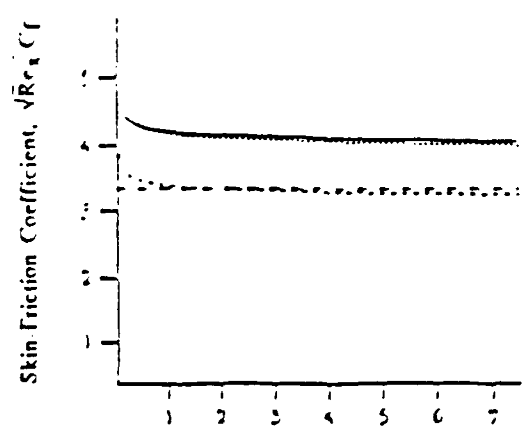
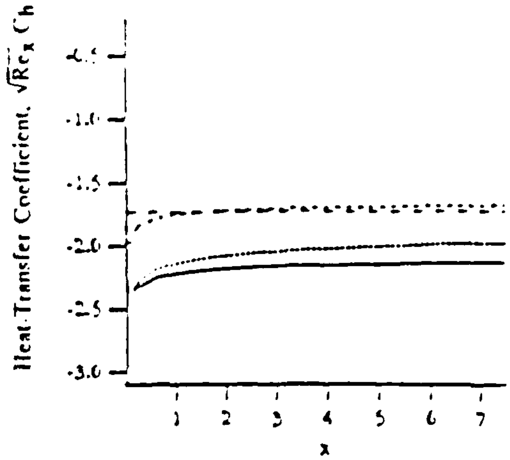
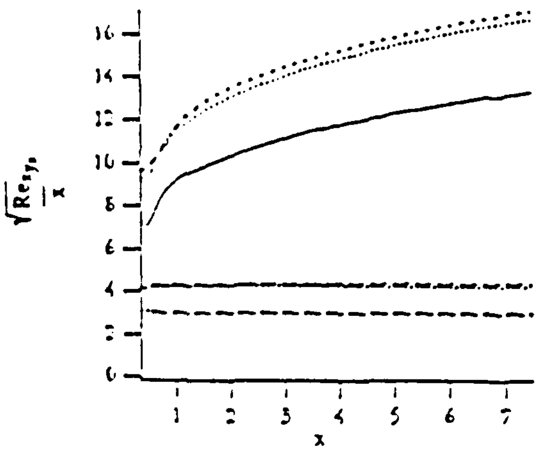
9. FIGURES



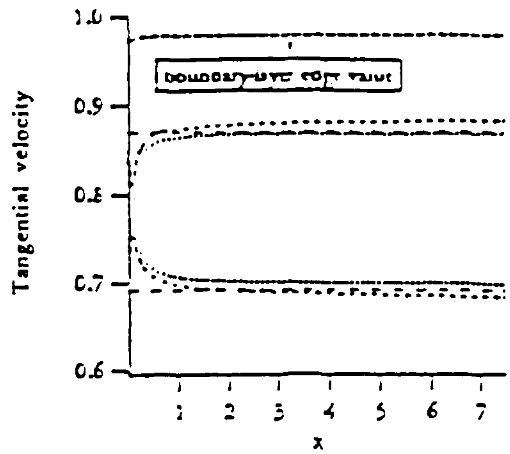
a) Skin-friction coefficient versus x



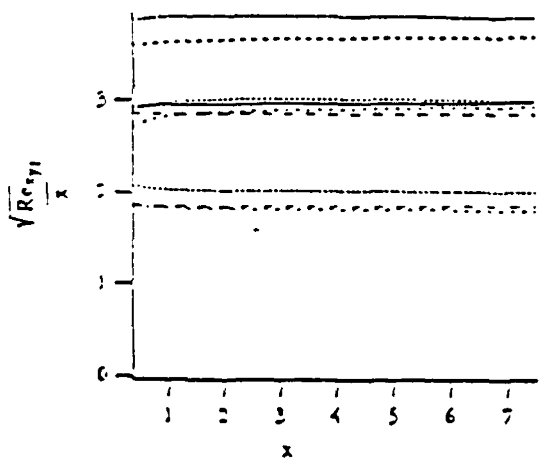
b) Heat-transfer coefficient versus x



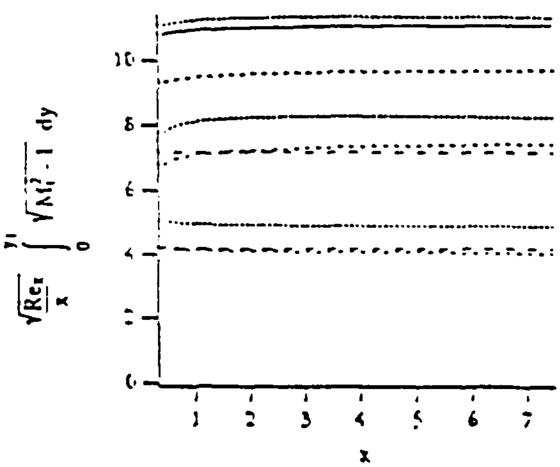
c) Locations of generalized inflection points



d) Tangential velocity at generalized inflection points



e) Location of relative sonic points for neutral disturbances



f) Neutral-disturbance wavenumber spacing integrals

Figure 1. Basic-state variations with respect to x

- · - Ideal Gas (Similarity Solution), ---- Ideal Gas (PNS),

— Equilibrium, ····· Nonequilibrium

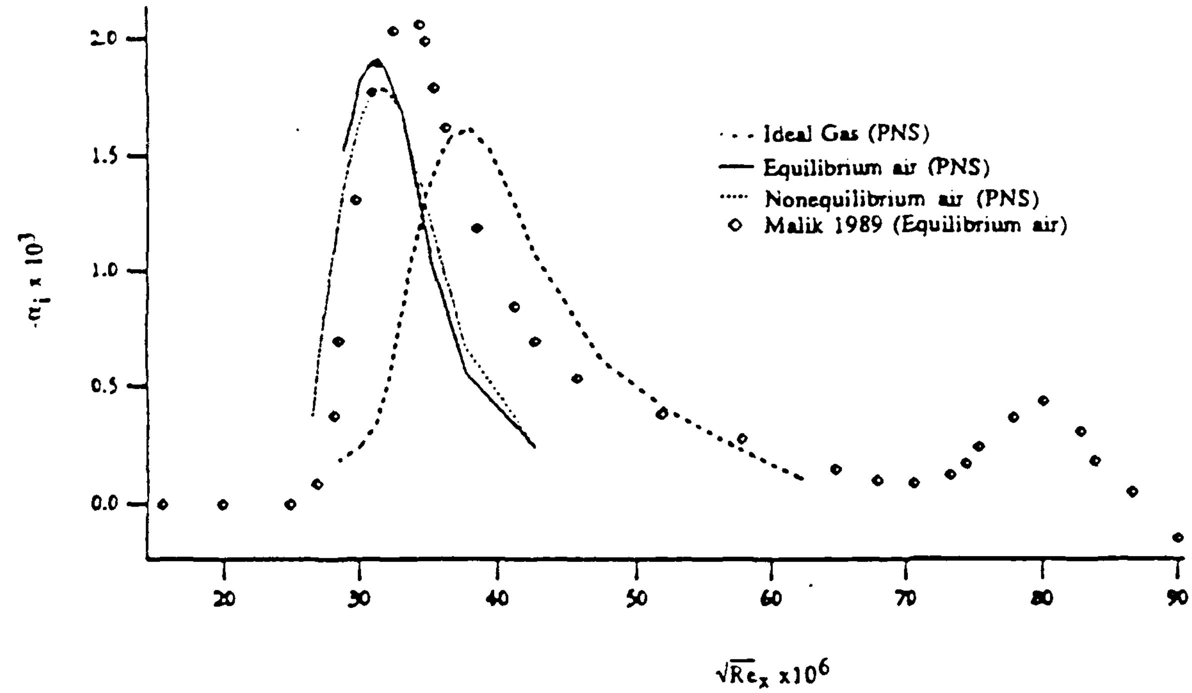


Figure 2. Adiabatic flat-plate boundary-layer disturbance-state amplification rates $\sqrt{Re_x}$ = 2000. Edge Mach number = 10.

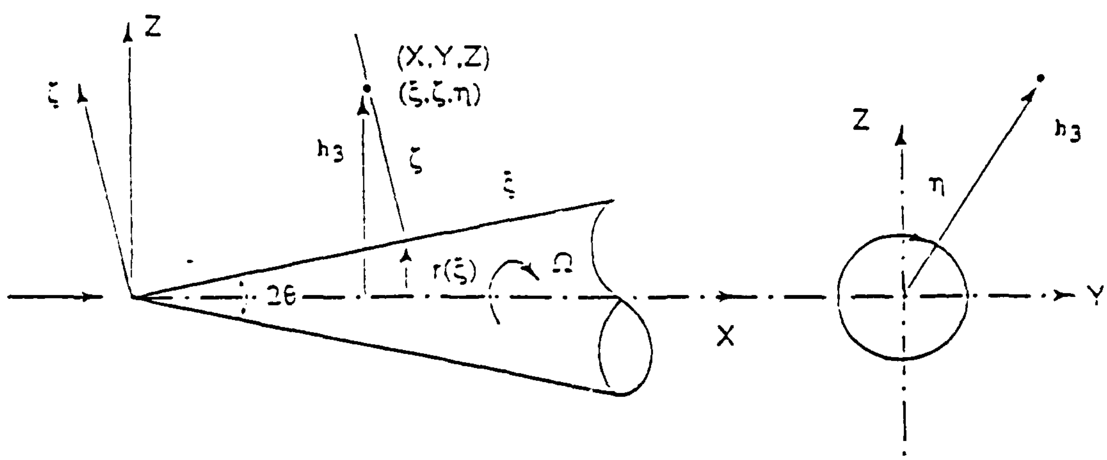


Figure 4. Rotating cone in supersonic axial flow and coordinate system.

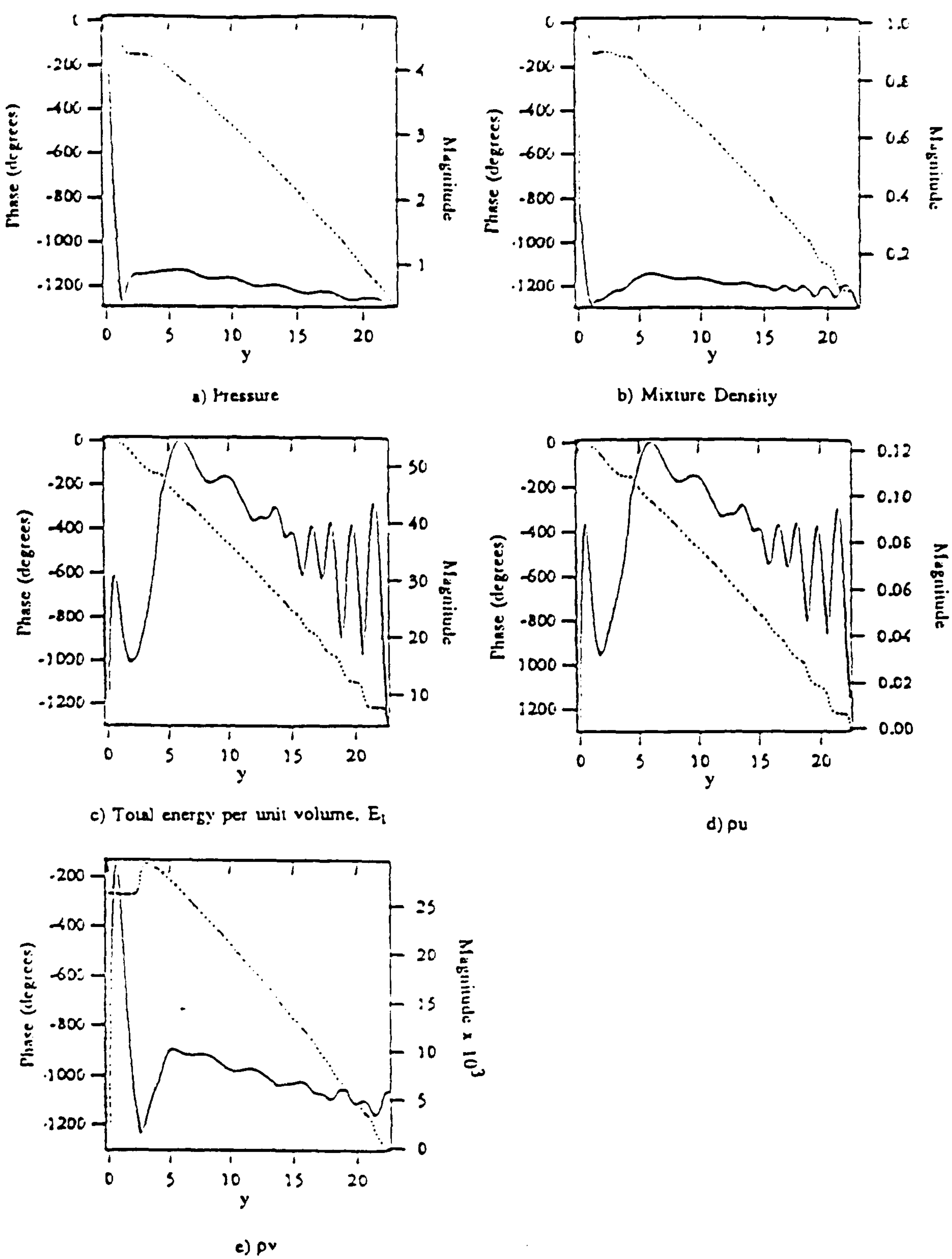


Figure 3. Equilibrium-air shock-layer disturbance-state eigenvector: —— magnitude, ······ phase; α = (0.364, -0.00415), β = (0,0), ω = (0.279, 0); $\sqrt{Re_x}$ = 1022.3.

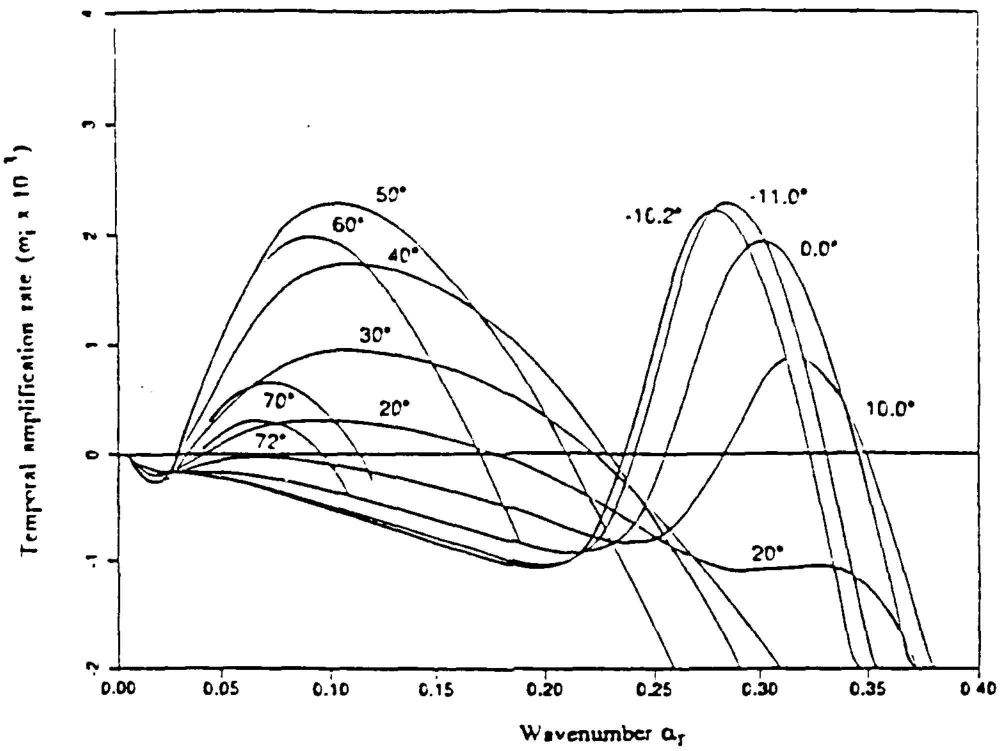


Figure 5. Distribution of amplification rate with wavenumber at $M = 5$, $Re = 600$ for different wave angles and with crossflow.

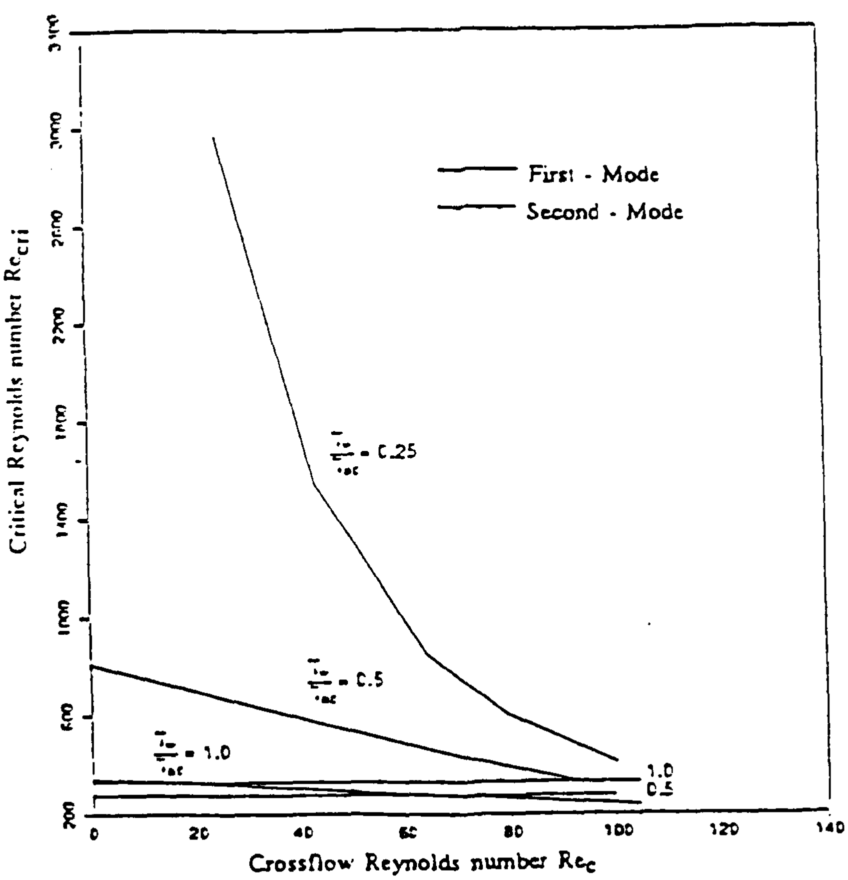


Figure 6. Variation of the critical Reynolds number Re_{cri} with the crossflow Reynolds number Re_c at $M = 5$.

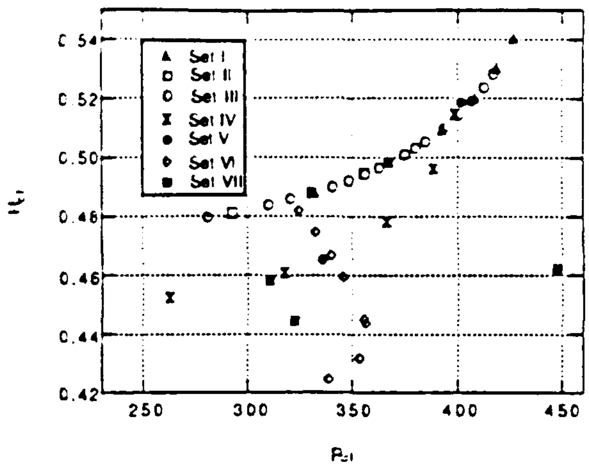


Figure 7. Traditional crossflow Reynolds number vs. shape factor at transition for various wall- and freestream-temperature conditions at M = 3.

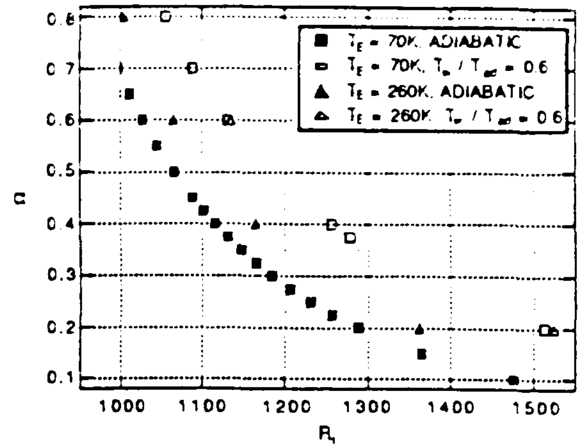


Figure 8. Transition Reynolds number vs. cone rotational speed for various wall- and freestream-temperature conditions at M = 3.

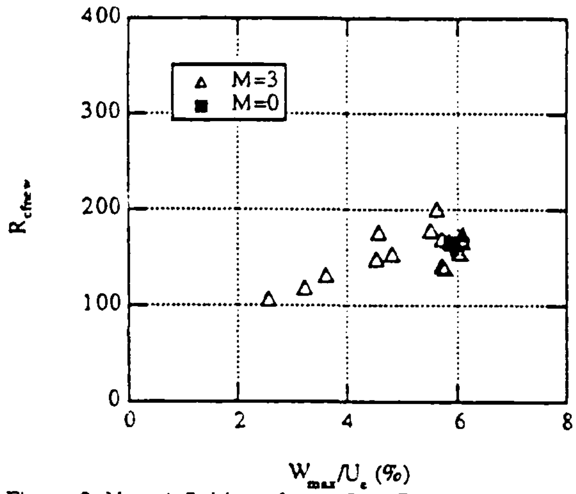


Figure 9. New definition of crossflow Reynolds number (including compressibility effects) versus maximum crossflow velocity for computational rotating-cone data assuming a transition location of N=9. Various freestream- and wall-temperature conditions as well as cone geometries are represented.

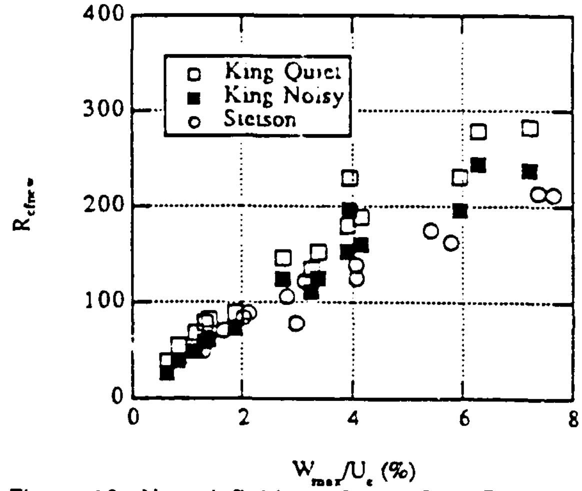


Figure 10. New definition of crossflow Reynolds number (including compressibility effects) versus maximum crossflow velocity for experimental yawed-cone data of King (1991) at M=3.5 and Stetson (1982) at M=5.9.

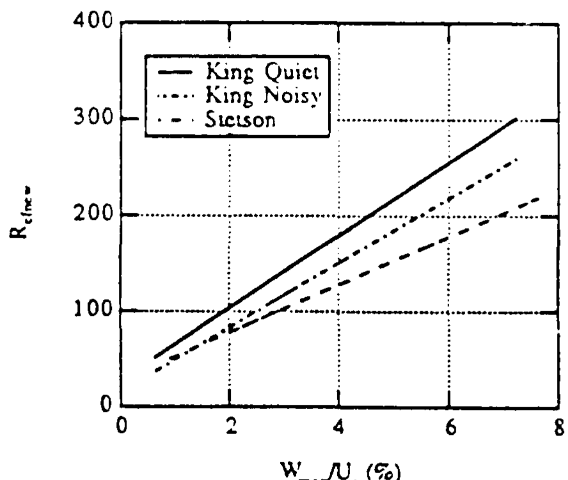


Figure 11. Linear least-squares approximation of new definition of crossflow Reynolds number (including compressibility effects) as a function of maximum crossflow velocity for experimental yawed-cone data of King (1991) at M=3.5 and Stetson (1982) at M=5.9.

10. AVAILABLE RESOURCES

One of the principal strengths of our team at Arizona State University is its broad skills in analysis, computations, and experiments. We facilitate day-to-day communication between the computational work and the experimental work through two IRIS Graphics Workstations (3030 and 3130) and two DEC-5000 Workstations. The system, with state-of-the-art, real-time, three-dimensional, color-graphics software (PLOT3D), is equipped with an extensive multi-user and multi-task environment with twelve serial lines. Users are able to share the same data base or experimental information. This provides the heart of the interaction of the analytical, computational, and experimental research.

In addition to the super computers at other National facilities, the network includes access to the IBM 4341/VM and Harris/VS computers, the IBM 3090 Class VI machine, and the Cray XMP on campus as well as the MASSCOMP. The College of Engineering at ASU is currently also equipped with several VAX/780 and VAX/785 minicomputers exclusively for research purposes (each office and laboratory has a hard-wired RS232 interface). These minicomputers are excellent systems for program development. The IRIS and DEC machines can access all the features available in those minicomputers through the existing local area networking (Ethernet) on the campus. Furthermore, the system can communicate directly with other research facilities to share information through telephone couplings. The full array of computer capabilities from super-mini to super-super was in place for this research.

APPENDIX A

HELEN LOUISE REED

1. *EDUCATION*

Ph.D., Engineering Mechanics, VPI&SU, Dec. 1981.

M.S., Engineering Mechanics, VPI&SU, June 1980.

A.B. in Mathematics, Goucher College, May 1977.

2. *AREA OF TEACHING AND RESEARCH*

Supersonics/Hypersonics, Hydrodynamic Stability, Laminar Flow Control, Three-Dimensional Boundary Layers, Receptivity, Separated and Transitional Flows, Unsteady Flows, Aerodynamics, Computational Fluid Mechanics, Perturbation Methods.

3. *POSITIONS HELD*

Aug. 1985 - present, Associate Professor (Tenure awarded Apr. 1988), ASU.

Sept. 1991-June 1992, Assoc. Prof. (Sabbatical), Inst. Fluid Sci., Tohoku Univ., Sendai, Japan.

Sept. 1982-Aug. 1985, Assistant Professor, Stanford Univ.

Jan. 1982-Aug. 1982, Assistant Professor (Non-tenure track), VPI&SU.

June 1977-Dec. 1981, Aerospace Technologist, NASA/Langley Research Center.

Summer 1976, Mathematics Aid, NASA/Langley Research Center.

4. *HONORS / DISTINCTIONS*

Phi Beta Kappa

Recipient of a NASA fellowship, 1976

Outstanding Summer Employee Award from NASA/Langley Research Center, 1976

Torrey Award for Excellence in Mathematics, Goucher College, 1977

Outstanding Achievement Award from NASA/Langley Research Center, 1978

Cunningham Fellowship Award from Virginia Polytechnic Institute & State Univ., 1981

Presidential Young Investigator Award, National Science Foundation, 1984

AIAA Excellence in Teaching Award, Arizona State University, Fall 1988

Professor of the Year, Pi Tau Sigma, Arizona State University, 1988-1989

Associate Fellow, American Institute of Aeronautics and Astronautics, December 1990

Faculty Awards for Women in Science and Engineering, National Science Foundation, 1991

5. *PUBLICATIONS*

"Flow over Plates with Suction through Porous Strips," A.H. Nayfeh, H.L. Reed, S.A. Ragab, *AIAA J.* 20,5,587, 1982.

"Stability of Flow over Axisymmetric Bodies with Porous Suction Strips," A.H. Nayfeh, H.L. Reed, *Phys. Fluids*, 28,10,2990, 1985.

"Numerical-Perturbation Technique for Stability of Flat-Plate Boundary Layers with Suction," H.L. Reed, A.H. Nayfeh, *AIAA J.*, 24,2,208, 1986.

"Effect of Suction and Weak Mass Injection on Boundary-Layer Transition," W.S. Saric, H.L. Reed, *AIAA J.*, 24,3,383, 1986.

"Flow over Bodies with Suction through Porous Strips," A.H. Nayfeh, H.L. Reed, S.A. Ragab, *Phys. Fluids*, 29,7,2042, 1986.

"Wave Interactions in Swept-Wing Flows," H.L. Reed, *Phys. Fluids*, 30,11,3419, 1987.

"Stability of Three-Dimensional Boundary Layers," H.L. Reed, W.S. Saric, *Ann. Rev. Fluid Mech.*, 21,235, 1989.

"Numerical Simulations of Transition in Oscillatory Plane Channel Flow," B.A. Singer, J.H. Ferziger, H.L. Reed, *JFM*, 208,45, 1989.

"The Effects of Streamwise Vortices on Transition in the Plane Channel," B.A. Singer, H.L. Reed, J.H. Ferziger, *Phys. Fluids A*, 1,12,1960, 1989.

"Compressible Boundary-Layer Stability Theory," H.L. Reed, P. Balakumar, *Phys. Fluids A*, 2,8,1341, 1990.

"An Application of Geometric Deformations Using Triparametric Volumes to Approximate Fluid Flow," S. Kersey, M. Henderson, H.L. Reed, R. Barnhill, acc. *Comp. Fluids*.

"Stability of Three-Dimensional Supersonic Boundary Layers," P. Balakumar, H.L. Reed, *Phys. Fluids A*, 3,4,617, 1991.

"A Catalogue of Linear Stability Theory Results," H.L. Reed, G. Gasperas, acc. *Ann. Rev. Fluid Mech.*, 26, 1994.

"Shepard's Interpolation for Solution-Adaptive Methods," C.-Y. Shen, H.L. Reed, T.A. Foley, acc. *J. Comp. Phys.*

"On the Linear Stability of Supersonic Cone Boundary Layers," G.K. Stuckert, H.L. Reed, acc. *AIAA J.*

"Application of a Solution-Adaptive Method to Fluid Flow: A Unified Approach," C.-Y. Shen, H.L. Reed, submit. *Comp. Fluids.*

"Development and Decay of a Pressure-Driven, Unsteady, Three-Dimensional Flow Separation," R.W. Henk, H.L. Reed, submit. *JFM*.

"Linear Disturbances in Hypersonic, Chemically Reacting Shock Layers," G.K. Stuckert, H.L. Reed, submit. *J. Comp. Phys.*

"Analysis of High-Frequency Secondary Instabilities in Three-Dimensional Boundary Layers," H.L. Reed, D.A. Fuciarelli, submit. *Phys. Fluids A*.

"A Numerical Model for Circulation Control Flows," R.G. Holz, A.A. Hassan, H.L. Reed, submit. *AIAA J.*

"Transition Correlation in Three-Dimensional Supersonic Boundary Layers," H.L. Reed, T.S. Haynes, submit. *AIAA J.*

"Curvature Effect on Stationary Crossflow Instability of a Three-Dimensional Boundary Layer," R.-S. Lin, H.L. Reed, submit. *AIAA J.*

37 refereed national conference proceedings papers (5 invited)

7 books and 7 articles edited

7 technical reports

6. *PROFESSIONAL SERVICE*

Member, Presidential Young Investigator Workshop on *U.S. Engineering, Mathematics, and Science Education for the Year 2010 and Beyond,* Wash., D.C., Nov. 4-6, 1990. This is an advisory group to President Bush's Science Advisor, Allen Bromley, concerning directions U.S. education *must* take for preparation and training of U.S.'s future scientists and lay people.

Member, *National Academy of Sciences/National Research Council Aerodynamics Panel* which is part of *Committee on Aeronautical Technologies of the Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems,* Nov. 1990-Mar. 1992. This is the advisory group to NASA and U.S. Congress concerning directions NASA *must* take in order to enable U.S. to remain competitive in world arena.

Member, *U.S. National Transition Study Group* under direction of Eli Reshotko, 1984-Pres.

Associate Editor, *Annual Review of Fluid Mechanics,* 1986-Present. With work divided equally among J. Lumley, M. Van Dyke, and myself, we are responsible for complete selection, refereeing, and editorial correction of all articles in each yearly volume.

Originator, *Annual Picture Gallery of Fluid Motions* at annual meetings of the *American Physical Society,* Nov. 1983, Houston. Responsibility for gallery at Brown University, Nov. 1984; Eugene, Nov. 1987; Buffalo, Nov. 1988; Palo Alto, Nov. 1989; Cornell, Nov. 1990; Scottsdale 1991.

Member, *AIAA Technical Committee on Fluid Dynamics,* 1984-1989.

Member, *Fluid Mechanics Technical Committee* of the *Applied Mechanics Division of the ASME,* 1984-Present.

University Representative, *National Science Foundation Fluids Engineering Workshop.* Group Leader and Coordinator of final document for Unsteady Flow Panel, Savannah, Sept. 17-20, 1986.

Chair, *ASME Junior Awards Committee* 1989-Present. Vice-Chair 1987-1988.

Member, Scientific Committee of 1992-3 *IUTAM Symposium on Nonlinear Stability of Nonparallel Flows,* Jan. 1990-Present.

Chair, *2nd Annual Arizona Fluid Mechanics Conference,* Arizona State University, Apr. 4-5, 1986.

Technical Chair, *AIAA 19th Fluid, Plasma Dynamics, and Lasers Conference,* Honolulu, June 1987.

Co-Chair, with Dan Jankowski, *44th Annual American Physical Society/Division of Fluid Dynamics Meeting,* Scottsdale, Nov. 1991.

Co-Organizer with Dr. Daniel Reda (Sandia National Laboratories) of *Symposium on Experimental and Theoretical/Numerical Studies of Boundary-Layer Stability and Transition,* at the *First Joint ASME/JSME Fluids Engineering Conference,* Portland, June 23-26, 1991.

Chair of 21 various symposia and sessions at international conferences.

CONSULTING

Westinghouse Electric and Naval Underwater Sea Center (1981)

Pratt and Whitney (1986-1991)

ICASE Consultant, NASA/Langley Research Center (Current)

EcoDynamics; Patrick Roache, President (Current)

APPENDIX B

WILLIAM S. SARIC
Professor

Degrees

Ph.D.	Illinois Institute of Technology, 1968
M.S.	University of New Mexico, 1965
B.S.	Illinois Institute of Technology, 1963

Academic Experience

1984-Present	Arizona State University, Professor, Mechanical and Aerospace Engineering Department
1979-1984	Virginia Polytechnic Institute and State University, Professor, Engineering Science and Mechanics
1975-1979	Virginia Polytechnic Institute and State University, Associate Professor
1966-1968	Illinois Institute of Technology, Instructor, Mechanics Department

Industrial Experience

1968-1975	Sandia National Laboratories, Staff Member, Atomic and Fluid Physics Division
1963-1966	Sandia National Laboratories, Staff Member, Reentry Vehicle Research Division
1957-1960	Dewey and Almy Chemical Co., W.R. Grace, Chicago, Chemical Mixer

Consulting Experience

Lawrence Livermore National Laboratories: Advanced Gas Centrifuge for Isotope Separation
Lockheed-Georgia, Marietta, Georgia: Laminar Flow Control and Transition
Sandia National Laboratories: Reentry Vehicle Aerodynamics

Professional Socities and Activities

American Inst. of Aero. & Astro., Assoc. Fellow
American Society for Engineering Education, Member
American Society of Mechanical Engineers, Member
Associate Editor, Applied Mechanics Reviews, 1984-present
Fellow, Japan Society for the Promotion of Sciences, 1989 - present
American Physical Society, Fellow
Tau Beta Pi (Honorary)
Pi Tau Sigma (Honorary)

Awards, Scholarships and Honor Societies

Alumni Award for Research Excellence, V.P.I. & S.U. 1984
Awarded Certificate of Teaching Excellence, V.P.I. & S.U. 1978
Invited Guest, U.S.S.R. Academy of Sciences 1984, 1981, 1979, 1976
Listed in *Who's Who in Aviation and Aerospace* (1st. Ed., U.S.) 1983
Listed in *American Men and Women in Science*, 1982
Winner, Flow Visualization, Poster Gallery Contest, 36th Annual Mtg. APS Div. Fluid Dyn. 1983

Principal Areas of Professional Interest

Theoretical and experimental studies in areas of hydrodynamic stability, boundary-layer transition, nonlinear waves, nonlinear dynamics, aerodynamics, laminar flow control, stability of stratified flows and perturbation methods.

Principal Publications and Papers 1980 - 1992

"Stability of Gortler Vortices in Boundary Layers," J.M. Floryan and W.S. Saric, *AIAA Journal*, Vol. 20, No. 3, 1982.
"Experiments on the Nonlinear Stability of Waves in a Boundary Layer," W.S. Saric and G.A. Reynolds, in *Laminar-Turbulent Transition*, Springer-Verlag, 1980.
"Wavelength Selection and Growth of Gortler Vortices," J.M. Floryan and W.S. Saric, *AIAA Journal*, Vol. 22, No. 11, 1984 and *AIAA Paper* No. 80-1376, 1980.
"Nonlinear Wave Interactions in Supersonic Wind-Generated Waves," S.G. Lekoudis, A.H. Nayfeh and W.S. Saric, *Phys. Fluids*, Vol. 25, No. 9, 1982.
"Effect of Suction on the Gortler Instability of Boundary Layers," J.M. Floryan and W.S. Saric, *AIAA Journal*, Vol. 21, No. 12, 1983.
"On the Visualization of Stream Structures in a Boundary Layer," (in Russian) A.V. Dovgal, V.V. Kozlov, I.P. Nosyrev and W.S. Saric, Preprint No. 37-81 of USSR Acad. Sci., Sib. Div., ITAM, *Izv. Akad. Nauk SSSR, Sib. Ot.*, 1982.
"An Orthogonal Coordinate Grid Following the Three-Dimensional Viscous Flow Over a Concave Surface," J.R. Dagenhart and W.S. Saric, *Proc. of Symposium on Grid Generation Techniques*, 1983.
"Experiments on the Subharmonic Route to Turbulence in Boundary Layers," W.S. Saric and A.S.W. Thomas, *Turbulence and Chaotic Phenomena in Fluids*, T. Tatsumi, North Holland, 1984.

"Formation of the Three-Dimensional Structure at Transition in a Boundary Layer," (in Russian) V.V. Kozlov, V. Ya. Levchenko and W.S. Saric, *Mekanika Zhidkosti i Gaza* No. 6, pp. 4250, Nov. 1984.
"Forced and Unforced Subharmonic Resonance in Boundary-Layer Transition," W.S. Saric, V.V. Kozlov and V. Ya. Levchenko, *AIAA Paper* No. 84-0007, 1984.
"Design of High-Reynolds-Number Flat Plate Experiments in the NTF," W.S. Saric and J.B. Peterson, *AIAA Paper* No. 84-0588, 1984.
"Generation of Crossflow Vortices in a Three-Dimensional Flat-Plate Flow," W.S. Saric and L.G. Yeates, *Laminar-Turbulent Transition*, V. Kozlov and V. Levchenko, eds., Springer-Verlag, 1985.
"Experiments on the Stability of Crossflow Vortices in Swept-Wing Flows," W.S. Saric and L.G. Yeates, *AIAA Paper* No. 85-0493, 1985.
"Boundary-Layer Transition: TS Waves and Crossflow Mechanisms", W.S. Saric, AGARD Report No. 723, 1985.
"Laminar Flow Control with Suction: Theory and Experiment," W.S. Saric, AGARD Report No. 723, 1985.
"Experiments on the Stability of a Flat-Plate Boundary Layer with Suction," G.A. Reynolds and W.S. Saric, *AIAA Journal*, Vol. 24, No. 2, 1986.
"Effect of Suction and Mass Injection on Boundary-Layer Transition," W.S. Saric and H.L. Reed, *AIAA Journal*, Vol. 24, No. 3, 1986.
"Oscillating Hot-Wire Measurements Above an FX63-137 Airfoil," J.D. Crouch and W.S. Saric, *AIAA Paper* No. 86-0012, 1986.
"Visualization of Different Transition Mechanisms," W.S. Saric, *Phys. Fluids, Vol. 29, No. 9*, 1986, p. 2770.
"Boundary Layer Transition to Turbulence: The last five years," W.S. Saric, *Proc. 10th Symposium on Turbulence*, September 1986.
"Three-Dimensional Stability of Boundary Layers," W.S. Saric and H.L. Reed, *Proc. Perspectives in Turbulence*, Eds: U. Meier and P. Bradshaw, Springer-Verlag, 1987.
"Fundamental Requirements for Freestream Turbulence Measurements," W.S. Saric, S. Takagi, and M.C. Mousseux, *AIAA Paper No. 88-0053*, January 1988.
"Stability of Three-Dimensional Boundary Layers," H.L. Reed and W.S. Saric, *Ann. Rev. Fluid Mech. Vol. 21*, 1989.
"Experiments in Swept-Wing Transition," W.S. Saric, J.R. Dagenhart, and M.C. Mousseux, *Numerical and Physical Aspects of Aerodynamic Flows, Vol. 4*, Ed: T. Cebeci, Springer-Verlag, 1989.
"Control of Random Disturbances in a Boundary Layer," P.T. Pupator and W.S. Saric, *AIAA Paper No. 89-1007*, March, 1989.
"Crossflow-Vortex Instability and Transition on a 45-Degree Swept Wing," J.R. Dagenhart, W.S. Saric, M.C. Mousseux, and J.P. Stack, *AIAA Paper No. 89-1892*, June, 1989.
"Boundary Layer Stability and Transition," W.S. Saric, *Proc. 5th International Conference on Numerical Ship Hydrodynamics*, Hiroshima, Japan, September 25-28, 1989.
"Experiments on Swept-Wing Boundary Layers," *Laminar-Turbulent Transition, vol. III*. eds. D. Arnal and R. Michel, Springer-Verlag, 1990.
"Comparison of Local and Marching Analyses of Görtler Instability," H.L. Day, T. Herbert, and W.S. Saric, *AIAA J., Vol. 28, No. 6*, 1990, pp 1010 - 1015.
"Boundary layer receptivity to sound: Navier-Stokes computations," H.L. Reed, N. Lin, and W.S. Saric, *Appl. Mech. Rev., vol 43, no. 5, part 2*, pp 175-180, May 1990.
"Measurements of Crossflow Vortices, Attachment-Line Flow, and Transition Using Microthin Hot Films," S.M. Mangalam, D.V. Maddalon, W.S. Saric,, and N.K. Agarwal, *AIAA Paper No. 90-1636*, June 1990.
"Low-Speed Experiments: Requirements for Stability Measurements," W. S. Saric, *Instability and Transition, Vol I*, Ed: Y. Hussaini, Springer-Verlag, 1990, pp 162 - 174.
"Boundary-Layer Receptivity: Navier-Stokes Computations,"N. Lin, H.L. Reed and W.S. Saric, Invited Paper, in *Proceedings* of the Eleventh U.S. National Congress of Applied Mechanics, ASME, New York, 45(5)pp 175-180, 1990.
"Experiments in Swept-Wing Transition," W.S. Saric, I.Ray Dagenhart, Marc C. Mousseux, *Numerical and Physical Aspects of Aerodynamic Flows IV*, ed T. Cebeci, Springer-Verlag, 1990.
"Comparison of Local and Marching Analyses of Görtler Instability," H.L. Day, T. Herbert, and W.S. Saric, *AIAA J.*, 28(9), 1990.
"A High Frequency Instability of Crossflow Vortices that leads to Transition," Y. Kohama, W.S. Saric, and J.A. Hoos, *Proc. RAS Conf. Boundary-Layer Transition and Control*, April 1991.
"Görtler Vortices With Periodic Curvature," W.S. Saric and A. Benmalek, *Proc. Boundary-Layer Stability and Transition to Turbulence*, June, 1991.
"Boundary Layer Receptivity to Sound with Roughness," W.S. Saric, J.A. Hoos, and R.H. Radeztsky, *Proc. Boundary-Layer Stability and Transition to Turbulence*, June, 1991.
"Görtler Vortices," W.S. Saric, *Ann. Rev. Fluid Mech. vol 25* 1993.